Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 9 (8): 1496-1502, 2009
ISSN 1812-5654

Development of a New Method for Tunnel Site Rating from Groundwater Hazard Point of View

H. Katibeh and A. Aalianvari
Department of Mining, Metallurgy and Petroleum, Amirkabir University, Tehran, Iran

Abstract: In this research, considering the experiments of tunnel inflow due to 10 different tunnels in Iran and adopting idea from site geomechanics rating like RMR, a new method has been developed for rating the tunnel site to evaluate the potential of tunnel inflow according to the preliminary investigation data. This method is called Site Groundwater Rating (SGR). Considered parameters in this method are: joint frequency, joint aperture, karstification, crashed zone, schistosity, head of water above tunnel, soil permeability and annual raining. Using these parameters and following SGR method, tunnel site can be categorized into six rates as follow: no risk, low risk, moderate risk, risky, high risk and critical. The method has been checked out with the observed groundwater inflow of Ghomroud tunnel and also, implied to rate the Amirkabir tunnel site in Iran.

Key words: Site rating, seepage, groundwater, tunnel site investigation

INTRODUCTION

One of the major practical difficulties often associated with tunnel construction is related to groundwater. In fact, some of the most disastrous experiences in tunneling have been the result of interception of large flows of water from highly fractured water-saturated rocks (Freeze and Cherry, 1979). In addition, prediction of groundwater inflow is needed to design suitable drainage systems.

Many researchers have paid attention to the problem of groundwater seepage into tunnels, however, most of the researches are around the computation of the quantity of groundwater inflow into tunnels such as Goodman *et al.* (1965), Lohman (1972), Zhang and Franklin (1993), Heuer (1995), Lei *et al.* (1999), Karlsrud (2001), Raymer (2001) and El Tani (2003).

One of the most important stages in preliminary investigation study of tunnel site is related to groundwater condition and its effects on tunnel during excavation and operation. There are various methods in site geomechanic rating like RMR, but there has been no any method in site groundwater rating till now. In this study, using the experiments due to ten tunnels in Iran, a new empirical method has been developed for rating the tunnel sites in groundwater hazard point of view, named Site Groundwater Rating (SGR). In this method, the tunnel site is categorized into six rates according to the preliminary investigations of engineering geological and hydrogeologic properties. For verification of this method, the results of SGR have been compared with the observed groundwater inflow in Ghomroud tunnel. Also, the method has been applied for rating the Amirkabir tunnel site.

MATERIALS AND METHODS

In this research work, according to an exact study of the geological and hydrogeologic features of 10 different tunnels (with the total length of about 16 km), the groundwater flow into tunnels has been related to the above mentioned features.

Tunnels considered in this research have been excavated in soil and rock. Rocks consist of shale, slate, sandstone, conglomerate, marl, granite, limestone and dolomite. From engineering geological point of view, different phenomena such as discontinuity, crashed zone, schistosity and karstification, are appeared in the above rocks. Also, hydrogeologic conditions in the tunnel paths have been studied and monitored exactly.

Compiling above data and comparing them with each other and finding proportional relation among them, tunnel sites have been rated into six different classes. According to the observations and experiments, the weighted factor of each geological and hydrogeologic feature on groundwater inflow has been considered in the proposed rating method. Using this method and relevant formula, SGR factor of tunnel site can be calculated. Finally, this factor guides the tunnel designers to the probable qualitative and quantitative idea about tunnel site from groundwater hazard point of view.

Corresponding Author: Homayoon Katibeh, Department of Mining, Metallurgy and Petroleum, Amirkabir University, Tehran, Iran

GOVERNING EQUATION ON GROUNDWATER FLOW

In its most basic form and for the case of laminar flow, Darcy's law links the water flow rate to the pressure gradient.

$$Q = KAi \tag{1}$$

Where:

Q = The flow rate ($m^3\ sec^{-1}$)
K = The hydraulic conductivity ($m\ sec^{-1}$)
A = The cross-sectional rock area (m^2)
i = The dimensionless hydraulic gradient

Flow of fluid along a single fracture depends on its hydraulic aperture, hydraulic gradient and its width. Following expression is for the flow rate, Q, along a single fracture:

$$Q = \frac{g e_h^3 b \Delta H}{12 \nu l} \tag{2}$$

where, Q is the flow rate along a single fracture ($m^3\ sec^{-1}$) of hydraulic aperture e_h (m), width b (m) and length l (m) under a total head loss ΔH (m) and in this equation ν is the kinematic viscosity of the fluid ($m^2\ sec^{-1}$) and g is the earth gravity ($m\ sec^{-2}$).

According to the Eq. 1 and 2 with increase in the cross section of groundwater inflow tunnel, the flow rate increases. In soil there is no very complexity, but in rock tunnels water flow is mostly related to the number of joints that tunnel crosses them and also the joint aperture. So, it is very important to identify the joint frequency and its aperture.

SITE GROUNDWATER RATING (SGR)

There are various parameters affecting the tunnel groundwater inflow, but in this research, the most important factors are considered as follow:

Joint frequency, joint aperture, karstification, crashed zone, schistosity, head of water above the tunnel, soil permeability and annual raining.

In SGR method, after scoring each parameter, the SGR factor of the site is computed and according to this factor the tunnel site is divided into six categories.

One of the advantages of this method is helping the engineers and contractors to design more suitable drainage systems and choosing the suitable drilling methods, according to the potential of the groundwater inflow, calculated in SGR.

In general, tunnel site are divided into two parts: tunnels in saturated zones and tunnels in unsaturated zones. Also with respect to the site lithology, tunnel sites are divided into rock sites and soil sites.

The equation to compute the SGR factor is:

$$SGR = [(S_1 + S_2 + S_3 + S_4) + S_5]S_6\ S_7 \tag{3}$$

where, parameters S_1 to S_7 respecting to the affecting parameters in groundwater inflow, will be described as below.

Score of frequency and aperture of joints, S_1: Massive rocks in tunnels alignment include one or more joint sets and tunnels cut them. Amount of water inflow into tunnels depends on joint frequency and joint aperture, so the representative parameter, S_1, is calculated using Eq. 4:

$$S_1 = 25 \times \left(\sum_{i=1}^{n} \frac{\lambda_i g e_i^2}{12\nu} a\right) \tag{4}$$

where, λ_i, the joint frequency (1/m), e_i, the mean hydraulic joint aperture (m) g, the earth gravity ($m\ sec^{-2}$), ν, the kinematic viscosity of water ($m^2\ sec^{-1}$), a, the unit factor ($sec\ m^{-1}$) converting S_1 to dimensionless form.

The constant coefficient in Eq. 4, 25, is obtained according to the experiments to normalize the parameter S_1.

The joint hydraulic aperture, e_h, in Eq. 4, is different from the joint aperture estimated in surface. Chen and Zhao (1998) suggested the following equation to calculate joint hydraulic aperture in depth:

$$e_{co} = E - \Delta V_j \tag{5}$$

where, E is average joint hydraulic aperture in surface (mm) and ΔV_j is calculated using the following equation:

$$\Delta V_j = \frac{\sigma_n V_m}{K_{ni} V_m + \sigma_n V_m} \tag{6}$$

where, Chen and Zhao (1998) suggested $\sigma_n = 0.027\ Z$, according to his experiments, in which Z is overburden thickness. Moreover, analysis by Bandis *et al*. (1983) of experimental data indicated that the following relation was appropriate

$$V_m = A + B(JRC) + C\left(\frac{JCS}{E}\right)^D \tag{7}$$

in which constants A, B, C and D, according to the Priest (1993) experimental researches are: A = -0.2960, B = -0.0056, C = 2.241 and D = -0.2450

JRC is joint roughness coefficient, JCS is joint wall strength and K_{ni} is computed using Eq. 8.

$$K_{ni} = 0.02(\frac{JCS}{E}) + 1.75JRC - 7.15 \tag{8}$$

Finally S_1 is calculated in dimensionless form. If the joint is filled with some materials such as clay, calcite, etc., then e_i will be equal to zero. However, the caution must be taken for the joints filled with washable materials such as some clay types. Joints with washable materials can be identified in the supplementary site investigation during Lugeon tests.

Schistosity, S_2: Commonly, clay-base rocks are supposed to schistosity during tectonic processes, so that water can flow through schist planes. However, the relevant permeability is very less compared to the other discontinuities. In spite of low permeability, in SGR, the parameter S_2, representative of schistosity, is supposed in the range of 1 to 5, depending on the degree of schistosity.

Crashed zone, S_3: Crashed zones are the major path of groundwater flow through rock. Crashed zones considerably increase rock permeability; however this increase depends on the rock type. In clay-base rocks such as marl, shale, schist etc, clay minerals fill fractures and discontinuities resulting in considerable decrease in the permeability of crashed zone, but in the other rock types such as limestone, the permeability in crashed zone is very high. Moreover, the groundwater flow rate through crashed zones is related to the rock type and the crashed zone width. Considering rock type and crashed zone width, Table 1 shows the equations to calculate S_3 in different rocks type in SGR.

Crashed zones in both saturated and unsaturated zones are suitable paths for groundwater flow, thus, crashed zones are of most important in SGR.

Karstification, S_4: Karstification is the geologic process of chemical and mechanical erosion by water on soluble bodies of rock, such as limestone, dolomite, gypsum, or salt, at or near the earth's surface. Karstification is exhibited best on thick, fractured and pure limestone in a humid environment in which the subsurface and surface are being modified simultaneously. The resulting karst morphology is usually characterized by some types of cavities and a complex subsurface drainage system. So these cavities can conduct groundwater into tunnels. Groundwater inflow into tunnels can be very sudden and so dangerous. According to the degree of karstification, S_4 is estimated between 10 to 100.

Table 1: Method to estimate S_3 in crashed zones

Type of rock	Crashed zone width	S_3
Clay base rocks	Czw	$2\times\text{Log}(10\ \text{Czw}\times b)$
Other rock type	Czw	$100\times\text{Log}(10\ \text{Czw}\times b)$

b is the unit factor (1/m), Czw is the crash zone width

Soil permeability, S_5: Parameters S_1 to S_4 are related to rock tunnels but if tunnel is excavated in soil, parameters S_1 to S_4 are automatically equal to zero. In SGR soil permeability is very important factor which is scored in S_5. The permeability of a clay layer can be as low as 10^{-10} m sec^{-1}, of a weakly permeable layer 10^{-6} m sec^{-1} and of a highly permeable layer 10^{-2} m sec^{-1}.

Because of the direct relation between soil permeability and rate of groundwater inflow, in SGR, the score of soil permeability, S_5 is calculated as follow:

$$S_5 = k \times c \tag{9}$$

where, k is the soil permeability (m day^{-1}), c is the unit factor (day m^{-1}) converting S_5 to dimensionless form.

Water head above tunnel, S_6: Head of water (H) above tunnel is one of the most effective parameters on groundwater inflow into tunnels. The inflow equations such as Muskat-Goodman, Rat-Schleiss-Lei, Karlsrud and Lombardi indicate that groundwater inflow into tunnel has linear relation with H/Ln (H) so the representative parameter S_6, is calculated using Eq. 10:

$$S_6 = \frac{H}{\text{Ln}(H \times d)} \times d \tag{10}$$

where, H is water head above tunnel and d is the unit factor (1/m) converting S_6 to dimensionless form. When tunnel is excavated above water table S_6 is equal to unit.

Annual raining, S_7: Just when tunnel is excavated in unsaturated zones, annual raining is effective on groundwater inflow into tunnels. In such case infiltrated water rain can seep into tunnel through fractures and faults. However, in such case groundwater inflow is not permanent like tunneling in saturated zones. Related to the tunnel depth, overburden permeability and length of water channel from discharging area up to tunnel, the time of reaching surface water to tunnel is different. In unsaturated zones quantity and intensity of raining affect the groundwater inflow into tunnels, but here only annual raining is considered. S_7 for unsaturated tunnels is calculated using Eq. 11:

$$S_7 = \frac{P_y}{5000} \qquad S_7 \leq 1 \tag{11}$$

where, P_y is annual raining (mm).

Maximum value of S_7 is when annual raining is equal to 5000 mm or more. When tunneling in saturated zone, $S_7 = 1$

Site Groundwater Rating (SGR): After calculating all the parameters, S_1 - S_7, SGR factor of the site is computed by means of Eq. 3, then according to the value of SGR and using Table 2, the tunnel site category can be found in six cases as: no danger, low danger, relatively dangerous, dangerous, highly dangerous and critical.

Experiments due to 10 tunnel show that there are direct correlation between SGR factor and groundwater inflow rate into tunnels. In case of high SGR factor (more than 700), mixture of mud and groundwater is probable to rush into tunnel, endangering persons and equipments.

In the other hand, with attention to SGR factor, groundwater inflow into tunnel can be predicted which help to plan suitable drainage systems and even to choose the best drilling method.

Table 2: SGR rating for groundwater inflow into tunnels

SGR	Tunnel rating	Class	Probable conditions for groundwater inflow into tunnel (L/sec/min)
0-100	No risk	I	0-0.04
100-300	Low risk	II	0.04-0.1
300-500	Moderate risk	III	0.1-0.16
500-700	Risky	IV	0.16-0.28
700-1000	High risk	V	Q>0.28' Inflow of groundwater and mud from crashed zones is probable
1000<	Critical	VI	Inflow of groundwater and mud is highly probable

VERIFICATION OF SGR USING OBSERVED GROUNDWATER DATA OF GHOMROUD TUNNEL

SGR method has been calibrated with the actual data obtained from Ghomroud tunnel. The 36 km Ghomroud tunnel is under drilling in order to convey water from Dez river basin to Ghomroud basin. Already about 6 km of tunnel has been drilled and the data of groundwater inflow due to this part has been recorded exactly.

The area under tunneling is located in Sannandaj-Sirjan zone of the geological divisions of Iran. This formation consists of series of asymmetric folding and faults and is gone through mild to high metamorphisms. The lithology of this area consists of a sequence of jurassic-cretaceous formation. The cretaceous formation consists of massive limestone and dolomite while the jurassic formation mainly consists of slate, schist and metamorphic shale and sandstone units. The majority of the rock mass is considered to be of weak to fair quality.

Only about 6 km of tunnel has been excavated and SGR factor is calculated for about 5 km of tunnel. Comparison of calculated SGR factor (based on surface and preliminary investigation) and observed data of groundwater inflow into Ghomroud tunnel has shown the direct relation between them and accuracy of SGR method. Geological features of Ghomroud tunnel are shown in Table 3.

Table 4 contains different geological zones of Ghomroud tunnel and calculated SGR factor for them and consequent rating.

As the Table 4 shows, according to SGR factor, crashed zones in limestone are the major problems in Ghomroud tunnel that can conduct large amount of

Table 3: Geological features of Ghomroud tunnel

Tunnel length (m)	Lithology	Head (m)	E (mm)	Joint No (i)	λ	Description
0-110	Slate, phyllite	20	0	0	0	Schistosity
110-135	Slate, phyllite	50	0	0	0	Crashed zone
135-835	Slate, phyllite	80	0	0	0	Schistosity
835-885	Slate, phyllite	80	0	0	0	Crashed zone
885-1125	Limestone	80	<1	2	6	Very low-low karstic
1125-1175	Limestone	90	0	0	0	Very low karstic (crashed zone)
1175-1455	Limestone	100	<1	2	4	Very low-low karstic
1455-1505	Limestone	120	0	0	0	Very low karstic (crashed zone)
1505-1845	Limestone	120	<1	3	3	Very low-low karstic
1845-1895	Limestone	120	1	0	0	Very low karstic (crashed zone)
1895-2795	Slate, phyllite	200	0	0	0	Schistosity
2795-2845	Slate, phyllite	200	0	0	0	Crashed zone
2845-3045	Slate, phyllite	200	0	0	0	Schistosity
3045-3145	Slate, phyllite	200	0	0	0	Crashed zone
3145-5000	Slate, phyllite	200	0	0	0	Schistosity

Table 4: SGR calculated for Ghomroud tunnel

Tunnel length (m)	S_1	S_2	S_3	S_4	S_5	S_6	S_7	SGR	Tunnel rating
0-110	0	3	0.00	0	0	7	1	21	No risk
110-135	0	3	4.79	0	0	12.78	1	99	No risk
135-835	0	3	0.00	0	0	18.26	1	55	No risk
835-885	0	3	5.40	0	0	18.26	1	153	Low risk
885-1125	3	0	0.00	20	0	18.26	1	420	Moderate risk
1125-1175	0	0	269.00	10	0	20.00	1	5580	Critical
1175-1455	3	0	0.00	20	0	21.71	1	470	Moderate risk
1455-1505	0	0	269.00	10	0	25.07	1	6980	Critical
1505-1845	3	1	0.00	20	0	25.07	1	600	Risky
1845-1895	0	1	269.00	10	0	25.07	1	7020	Critical
1895-2795	0	3	0.00	0	0	37.75	1	113	Low risk
2795-2845	0	3	5.40	0	0	37.75	1	317	Moderate risk
2845-3045	0	3	0.00	0	0	37.75	1	113	Low risk
3045-3145	0	3	6.00	0	0	37.75	1	339	Moderate risk
3145-5000	0	3	0.00	0	0	37.75	1	113	Low risk

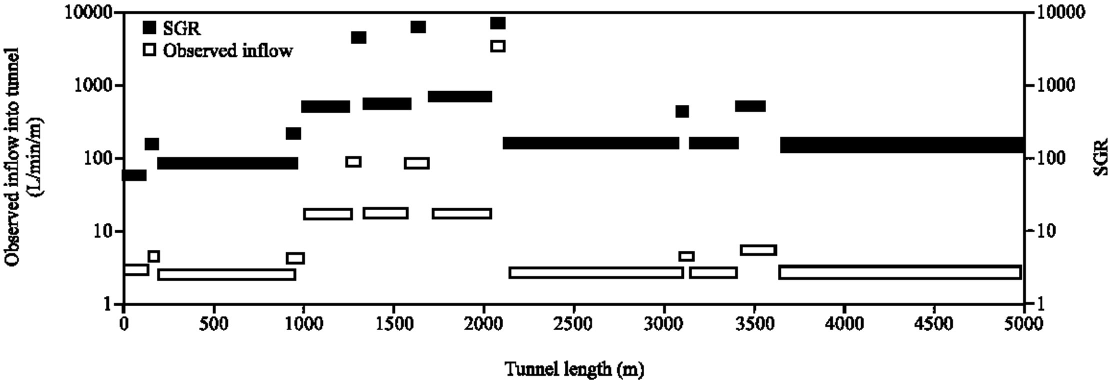

Fig. 1: Relation between SGR and observed groundwater inflow into Ghomroud tunnel

groundwater into the tunnel. In Fig. 1, the SGR results have been compared with the actual observation of groundwater inflow for each geological zone of the tunnel. As the figure shows, direct relation between SGR factors and observed inflow can be seen which indicate the accuracy of SGR in rating the tunnel site in groundwater inflow point of view.

Based on the Fig. 1, most of the inflow takes place through a small portion of the tunnel length conforming on the crashed zones and the remaining of the inflow takes place through a large portion of tunnel. As Table 4 shows, most of the crashed zones in limestone, are rated in the category of highly dangerous-critical in SGR. Such a rating is in very close accordance with the observed groundwater inflow. Observations showed that total volume of water inflow into tunnel from limestone (a long 1000 m of the tunnel length) is about 25 L sec^{-1} (1500 L min^{-1}) that is relatively high and in the other parts of tunnel that consist of schist-slate sequences layer (Anvari and Katibeh, 2006) water inflow is very less as SGR factor either showed that.

AMIRKABIR TUNNEL SITE RATING USING SGR

The 30 km water conveying tunnel, named Amirkabir is supposed to be drilled in Alborz mountain range in Iran. In this study, SGR has been applied for rating 6 km of this tunnel according to preliminary and surface investigations. The area under study is located in Karaj formation consisting of complex sedimentary and volcanic rocks such as monzodiorite, gabro, tuff, sandstone and conglomerate limestone. In the geological point of view, the tunnel crosses three geologic units as GTA1, (monzodiorite, gabro), GTA2, (sandstone, tuff) and GTA3, (massive conglomerate, green tuff, massive limestone). Table 5 shows geological features of Amirkabir tunnel for its first 6 km.

With attention to parameters such as joint aperture, tunnel depth, water head and crashed zones in Amirkabir tunnel path, Table 6 shows the calculated SGR for different geological zones.

Table 5: Discontinuity of Amirkabir tunnel (first 6 km)

Lithology	Discontinuity	Aperture (mm)	λ	JRC	JCS (MPa)
Monzodiorite, Gabro	J1	<1	6	8-10	22
	J2	<1	4	8-10	25
	J3	1-3	6	2-4	25
	B	Fill	3	8-10	22
Tuff, Sandstone	J1	<1	3	8-10	60
	J2	<1	4	2-4	60
	B	Fill	2	8-10	60
Conglomerate limestone	J1	Fill	2	10-12	90
	J2	<1	3	8-12	90
	B	Fill	1	10-12	90

Table 6: Calculated SGR for Amirkabir tunnel

Tunnel length (m)	Lithology	Head (m)	S_1	S_3	S_6	S_7	SGR	Tunnel rating
0-450	Monzodiorite, Gabro	0	64	0	1	0.2	13	No risk
450-550	Monzodiorite, Gabro	0	0	300	1	0.2	60	No risk
550-2000	Monzodiorite, Gabro	0	64	0	1	0.2	13	No risk
2000-2250	Monzodiorite, Gabro	2	61	0	3	1.0	179	Low risk
2250-2300	Monzodiorite, Gabro	2	0	270	3	1.0	781	High risk
2300-2800	Tuff, sandstone	20	6	0	7	1.0	45	No risk
2800-3050	Tuff, sandstone	50	0	339	13	1.0	4345	Critical
3050-3850	Tuff, sandstone	200	5	0	38	1.0	241	Low risk
3850-3900	Tuff, sandstone	200	0	270	38	1.0	10229	Critical
3900-4600	Tuff, sandstone	200	5	0	38	1.0	241	Low risk
4600-4700	Tuff, sandstone	200	0	300	38	1.0	11362	Critical
4700-6000	Conglomerate limestone	200	2	0	38	1.0	113	Low risk

S_2, S_4 and S_5 are equal to zero for all 6 km

In the first 6 km of Amirkabir tunnel, base on the results obtained from SGR, the major problem is appeared in to crashed zones (area about main faults) which are categorized in highly dangerous and critical zones. So in these zones caution must be taken in drainage systems planning, drilling method and supports.

CONCLUSION

Considering the experiments of tunnel inflow due to 10 different tunnels in Iran a new method has been developed for rating tunnel site to evaluate the potential of groundwater inflow according to the preliminary investigation data. This method is called Site Groundwater Rating (SGR). Using the method, tunnel site can be categorized into six rates. Studies showed that there is good accordance between SGR factor and groundwater inflow rate into tunnels. The method has been examined in Ghomroud tunnel and applied for Amirkabir tunnel. Applying SGR method according to preliminary investigations conducts designers to more suitable design of drainage system, drilling method and roof supports.

ACKNOWLEDGMENTS

Hereby, the authors express their thanks to the Transportation Research Institute of the Ministry of Road and Transportation of Iran for its generous helps throughout this research.

REFERENCES

Anvari, A.A. and H. Katibeh, 2006. Estimation of groundwater inflow into qomroud water supply tunnel using plaxis software. 6th Congress on Safety, Health and Environment in Mines and Related Industries. http://www.civilica.com/EnPaper-SHEMRI06-SHEMRI06_010.html.

Bandis, S.C., A.C. Lumsden and N.R. Barton, 1983. Experimental studies of scale effects on the shear behavior of rock joints. Int. J. Rock Mech. Min. Sci. Geomech. Abstr., 18: 1-21.

Chen, S.G. and J. Zhao, 1998. A study of UDEC modelling for blast wave propagation in jointed rock masses. Int. J. Rock Mech. Min. Sci., 35: 93-99.

El Tani, M., 2003. Circular tunnel in a semi-infinite aquifer. Tunnel. Underground Space Technol., 18: 49-55.

Freeze, R.A. and J.A. Cherry, 1979. Groundwater Englewood. Prentice-Hall Inc., New Jersey.

Goodman, R.E., D.G. Moye, A. Van Schalkwyk and I. Javandel, 1965. Ground water inflows during tunnel driving. Bull. Assoc. Eng. Geologists, 2: 35-56.

Heuer, R.E., 1995. Estimating rock tunnel water inflow. RETC Proceedings, Chapter 3, pp: 41-60.

Karlsrud, K., 2001. Water control when tunnelling under urban areas in the olso region. NFF Publication No. 12, 4, 27-33, NFF.

Lei, S., 1999. An analytical solution for steady flow into a tunnel. Ground Water, 37: 23-26.

Lohman, S.W., 1972. Ground-water hydraulics. US Geological Survey, Professional Paper 708.

Priest, S., 1993. Discontinuity Analysis for Rock Engineering. 1st Edn., Chapman and Hall, London.

Raymer, J.H., 2001. Predicting groundwater inflow into hard-rock tunnels: Estimating the high-end of the permeability distribution. Proceedings of the Rapid Excavation and Tunnelling Conference, Society for Mining, Metallurgy and Exploration, Inc.

Zhang, L. and J.A. Franklin, 1993. Prediction of water flow into rock tunnels: An analytical solution assuming a hydraulic conductivity gradient. Int. J. Rock Mech. Min. Sci., Abstr., 30: 37-46.